LIMITED REPORT

Past Climate Changes of the Canadian Prairie Provinces

by

E. Wheaton

Environment Branch

SRC Publication No. 11341-1E01

technology is our business

June, 2001

LIMITED REPORT

Past Climate Changes of the Canadian Prairie Provinces

by

E. Wheaton

Environment Branch

Saskatchewan Research Council
15 Innovation Blvd.
Saskatoon, SK S7N 2X8
Phone: 306-933-7432
Fax: 306-933-7817

SRC Publication No. 11341-1E01

June, 2001

TABLE OF CONTENTS

page

LIST OF FIGURES

INTRODUCTION AND OBJECTIVES

The climate of the Canadian Prairie Provinces has undergone significant changes in the past century. Past trends of several climatic elements are discussed here to provide the context for future possible changes described in a companion paper (Wheaton and Wittrock 2001). Knowledge of past climatic trends is very important in understanding past ecosystem and socio-economic linkages and effects. Past high emissions of greenhouse gases have already caused regional and global warming, and more rapid climatic changes are expected for the future.

Most of the Prairie Provinces is classified into two main climate regions for ease of description of trends (Figure 1). These regions are the prairie region, which is mainly the agriculture and grassland climatic region, and the northwestern boreal forest climate region. The former is often shortened to "grasslands," and the latter is referred to as "forest region."

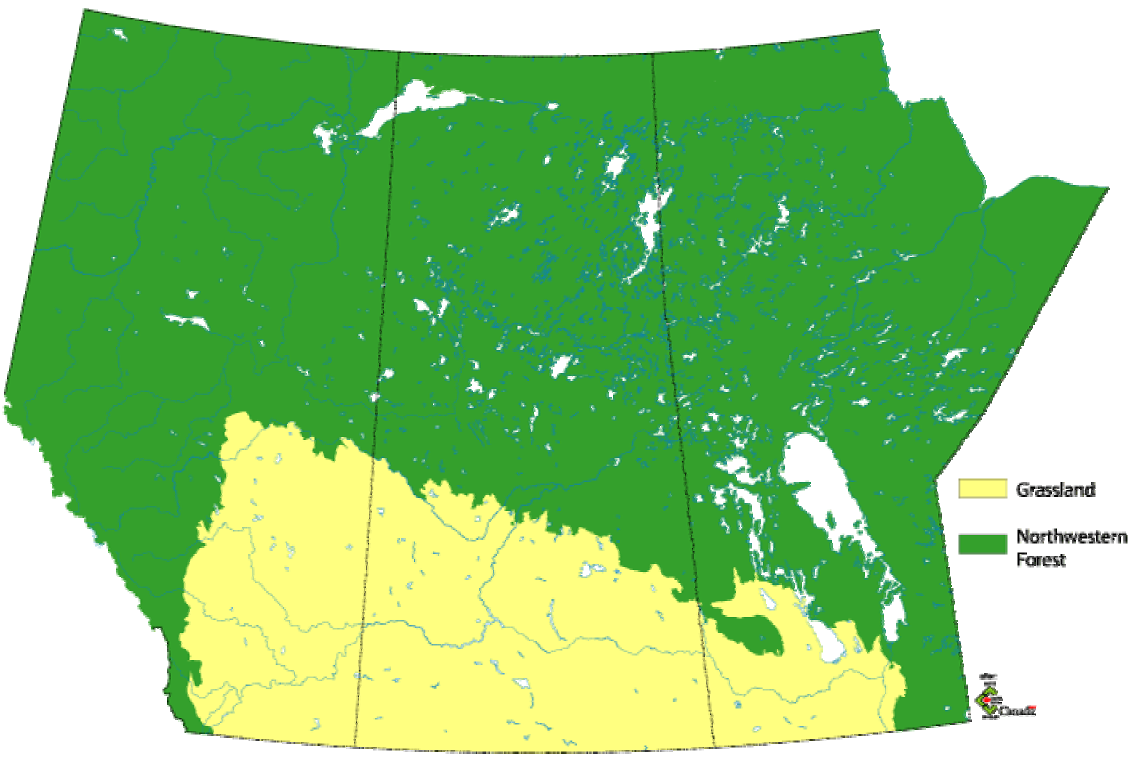

Figure 1: Grassland and Forest Climate Regions of the Canadian Prairie Provinces (Environment Canada 1995)

Objectives and Scope

The objectives of this paper are to briefly describe and discuss highlights of climate change in the past century. The study area is the Canadian Prairie Provinces, termed the Prairies here. The main climatic elements of temperature and precipitation are emphasized. Variables affected by air temperature are discussed, including ground temperatures, frost-free season, lake ice cover, snow cover, and glacier cover. An overview of some ecological implications of temperature changes is provided. Trends in extreme events are examined, where information is available. These extremes include hot and cold spells, dry and wet spells, and storms, such as dust storms, hail storms, and tornados.

CHANGES IN TEMPERATURE AND RELATED VARIABLES

Temperature is the climatic element that has undergone some of the most dramatic changes, especially in the Prairies. The main temperature changes during 1895 to 1991 for the Prairies include (Environment Canada 1995):

- a statistically significant increase in **annual** average temperature of 0.9 °C for the prairie climate region to 1.4°C for the forest climatic region.
- statistically significant temperature increases of 1.3 to 2.1°C have occurred in the **spring** (March, April, May). Increases of 0.7 to 1.2°C have occurred in the **summer** (June, July, August) for both the grassland and forest climatic regions. The larger increases are for the forest region.
- **winter** (December, January, February) has had fairly large, but not statistically significant increases of 1.5 to 1.7°C. **Fall** (September, October, November) experienced increases of 0.2 to 0.4°C . Again, the larger increases are for the forest region.
- statistically significant increases of 1.3 to 2.1° C were found in the daily minimum temperatures, but increases in daily maxima were not significant. These changes result in a decrease in the **daily temperature range**.

These trends clearly demonstrate that warming dominates for the Prairies. This warming has not been uniform in time, area, or rate. Neither should we expect future changes to be uniform.

More recent work by Zhang et al. (2000) using the best available data updates and confirms the above findings. Their conclusions support the reality of these warming trends. Updated highlights of the temperature change over 1900 to 1998 are:

- mean daily **maximum temperature** exhibits the greatest warming (statistically significant) in the Prairie Provinces as compared to the rest of Canada, with the greatest warming in Saskatchewan at about 1.5°C for the annual value (Figure 2). The season of greatest warming is **spring**, with winter a close second, but not statistically significant. The warming in summer is about 1.0°C and it is significant.
- again, the greatest increase in the mean daily **minimum temperature** in Canada is in the Prairies, at about 1.5°C for the annual values (Figure 3). The highest rates of the Prairies are in Saskatchewan in the grassland region, especially for **winter**, at about 3.0°C. **Fall** increases are highest for all Canada in Alberta and Saskatchewan in the forest region at about 3.0°C.
- significant decreases in the **daily temperature range** of about 0.5°C (annual average) have occurred. This change is a result of the more rapid increases in the daily minimum temperatures as compared to the maxima.

It is useful to compare these temperature changes to those over several hundreds of years to determine how extreme they are. Luckman (1998) used a tree-ring-based reconstructed record for comparison in the central Canadian Rockies. Summer and spring temperatures in the last fifty years are higher than any equivalent period over the past 900 years. Luckman (1998) used other environmental evidence to show that the climate of the late 20th century is exceptional in terms of an even longer period, the past 1000 to 3000 years.

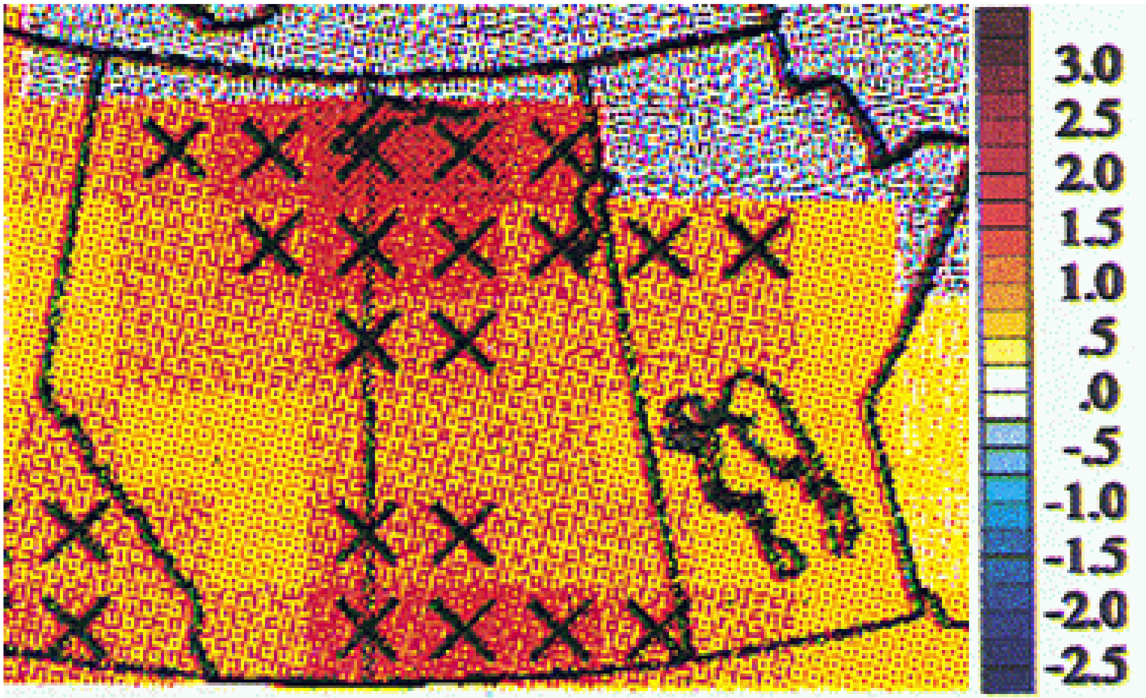

Figure 2: **Trends in daily maximum temperature from 1900-1998 (annual)** (after Zhang et al. 2000:407). Units are /C per 99-year period. Statistically significant trends are marked with crosses.

Figure 3: **Trends in daily minimum temperature from 1900-1998 (annual)** (after Zhang et al. 2000:409). Units are /C per 99-year period. Statistically significant trends are marked with crosses.

The air temperature increases are further substantiated by **ground surface temperature** changes measured in wells. Patterns of temperature in the upper soil layers over time and space in the Prairies also show considerable increases over the past several decades (Majorowicz and Skinner 1997). The annual ground surface temperature change for 1950-1990 ranges from lows near 0°C in southwestern Alberta and northern Manitoba to increases greater than 3.5°C in the northeastern Alberta. A broad corridor from southwestern Manitoba into northeastern Alberta has the greatest change. These changes are thought to be driven by both air temperature increases and by land-use changes.

General increases in the **frost-free season length** also reflect these strong temperature trends. Trend information is only available for the grassland region of the Prairies. Trends in the frost-free season in the boreal forest of the Prairies have not been documented, to the author's knowledge. The average frost-free season length in the grassland region for the 1946 to 1955 period ranged from about 95 days in the north to about 115 days in the south. During the 1986 to 1995 period the average length increased about 10 days to produce a range of about 105 days in the north to more than 125 days in the southwest (Lemmen et al. 2000).

Measures of accumulated temperatures such as **growing degree-days** are used as indicators of plant zonation (e.g. Singh and Wheaton 1991), plant maturation potentials and plant and animal phenology. No documentation of trends was found for accumulated temperature indices and this work remains a research gap.

Lake ice cover break-up and freeze-up are also particularly sensitive to temperature. The trend in dates by which lakes are free of ice is consistent with the change to warmer winters and springs. Two sample lakes in the forest climatic region of the study area show trends of about a week earlier ice breakup dates by the mid-1990s as compared to the late 1950s and 1960s (Environment Canada 1995).

Thus considerable evidence is accumulating to demonstrate that the air temperature increases are general and very real, as seen by these ripple effects through related physical changes as with lake ice break-up and soil temperatures. The databases used are of good quality and carefully checked to minimize effects of changes in location, instrumentation, and urban heat island, for example.

NATIONAL AND GLOBAL CONTEXT

Some of the most dramatic temperature changes in Canada, and perhaps the world, have been experienced in the Prairies. These changes have occurred within the setting of national and global changes. Canada's mean temperature increased by about 1.0°C over the last 100 years (Gullet and Skinner 1992). The minimum temperature has increased by more than twice the rate of the maximum temperature for southern Canada (Vincent et al. 1999).

The global annual average temperature has increased about 0.6° C in the last century. The global temperature has risen faster in the past 20 years than in any other 20 year period on record (World Meteorological Organization 1999). This trend appears to be accelerating as the 1990s was the warmest decade of the past five centuries. Observed warming in the 1900s is significantly above natural variability, as demonstrated by both paleoclimate and Global Climate Model (GCM) estimates of natural variability (Grassl 2000). A change point in global temperature trends occurred since 1976 when the rate of change became greater than the mean rate of warming averaged over the late 19th and 20th Centuries. Some of the warmest years on record have occurred during the 1990s, i.e. 1995, 1990, 1997 and 1998. This is likely an indicator of an increase in the rate of global warming (Karl et al. 2000). This is a remarkable string of records. Thus, strong regional and global warming is already occurring.

Greater effort is being invested in exploring the causes of these global and regional changes. Numerous analyses demonstrate that the increasing greenhouse gases are the dominant climate change driver in the last century, and the likely dominant factor for the next century. Although the causes of these climatic trends are a result of several factors, Watson et al. (2001) point out the close correspondence between observed trends and those estimated by the GCMs, when forced with historical greenhouse gas increases as well as natural factors.

By 1996, the Intergovernmental Panel on Climate Change [IPCC] stated that the "balance of evidence suggests a discernible human influence on global climate change" (Houghton et al. 1996). New and stronger evidence in the Third Assessment Report of the IPCC has confirmed this finding. The evidence shows that most of the warming over the past 50 years is attributable to human activities (Watson et al. 2001). Past high and continuing high greenhouse gas emissions are committing the Earth to a path of human-induced climate change.

The global temperature changes may appear small, and indeed are smaller than the Prairie changes, but they are significant on a climatological, global, and ecological bases. A small change in global temperature translates into large regional and daily changes, with record-setting events. The average global temperature difference between an ice age and an inter-glacial age, for example, is only about 4 to 6°C. An increase of 1°C globally would result in regional temperatures the Earth has not experienced for at least 160,000 years (Hengeveld 1995).

Further, small increases in average monthly temperatures make a large difference in extreme daily temperatures. For example, an increase of only about 4°C in mean monthly temperatures in May 1988 resulted in both severe droughts and in heat waves with near-record daily temperatures over 40°C in many stations in Saskatchewan (Wheaton 1991).

ECOLOGICAL IMPLICATIONS

Ecosystems are especially sensitive to small changes in average temperature. For example, the average annual temperature of the parkland, the grassland to forest transition zone, is only about 2°C higher than that of the forest region (Singh and Wheaton 1991). Climate is the major factor affecting the distribution of natural vegetation.

The IPCC Working Group II on impacts and vulnerability has compiled information from many studies showing that the warming has already begun to affect ecosystems with measurable impacts. Forty-four regional studies of over 400 plants and animals have documented examples of changes. Recent regional changes in temperature have had discernible impacts on many physical and biological systems. IPCC gives a high confidence rating to this finding on the basis of observational evidence, modelling results and theory (Ahmad et al. 2001).

An example of an ecosystem change is that plant growth is documented to have increased in northern high latitudes during 1981 to 1991 as indicated by remote sensing data (Myneni et al. 1997). The biophysical changes driving the increased plant growth are the ones discussed here, including marked warming in the spring, lengthening of growing season, and longer snow-free season.

A regional example of vegetation change in response to climate changes is that of the upper tree-line ecotone in the central Canadian Rockies during the 20th Century. Change is more readily detected at ecotones. Luckman and Kavanagh (1998) found extensive up-slope migration of the treeline by the process of seedling establishment. Thus small, but significant climate-affected changes are taking place in vegetation zonation.

Vegetation is very sensitive to temperature variations in spring, and this effect shows up in phenology, or timing of events such as blooming. Plant phenology data are an indicator of the effect of climate and are also an indicator of changes in such effects. Phenology changes are useful for monitoring the impact of climate variations. An average 5-6 day advance toward earlier springs has occurred in North America during 1959-1993, as evidenced by lilac phenological data. The strongest regional patterns of earlier springs were found in northwestern US and southwestern Canada (Schwartz and Reiter 2000). These trends compare well with the 6 day advance found for Europe (Menzel and Fabian 1999).

Phenology research in Alberta has shown that a trend to a 26 day earlier shift in spring blooming dates for aspen poplar (*Populus tremuloides*) over the last century (Beaubien and Freeland 2000). The timing of spring growth phases, such as budding, is primarily driven by accumulated temperatures above certain thresholds. Beaubien and Freeland (2000) note a couple of concerns about such changes. One concern is that normal development of plants may be disrupted as the thermal regime is changing without corresponding changes in photoperiod. Another concern is that earlier blooming may be leading to increased risk of frosts and the loss of the year's seed production. A research gap noted is the lack of fall phenological data and trend work.

Phenological changes are not only being found for plants, but wildlife is also being affected by climate changes. Earlier bird arrival, breeding dates, and earlier emergence of insects have been documented for the Northern Hemisphere (Watson et al. 2001). For example, the North American tree swallow nesting times have also advanced over a similar period (Dunn and Winkler 1999). A Prairie example is that waterfowl and their wetland habitat suffered extreme losses because of the dry climate of the 1980s (Wittrock and Wheaton 1989). Droughts were linked with decreasing numbers and quality of wetlands and of duck populations. There are likely many more changes that have not been monitored or documented. Many more changes are expected to occur.

PRECIPITATION AND OTHER HYDROLOGICAL TRENDS

Precipitation is much more variable than temperature both spatially and temporally, and trends are less clear (Environment Canada 1995). However, analyses show (Zhang et al. 2000):

- **annual precipitation** totals have a negligible to about 15% increase over the Prairies (Figure 4). Generally only the northern parts of the forest region and most of Manitoba have statistically significant and also larger values. The extreme southeast corner of Saskatchewan shows little or no change. In contrast, national annual precipitation averages have more rapid increases of 5-30%.

- **winter**, then fall have the strongest increases seasonally. Winter has increases of over 25% for much of the forest region. **Summer** generally shows little change to increases of about 10% over much of the Prairies, to decreases of about 5% in southern Saskatchewan.
- the ratio of **snow to total precipitation** shows more complex spatial patterns of little change to some increases for annual values, but none of the trends are statistically significant.

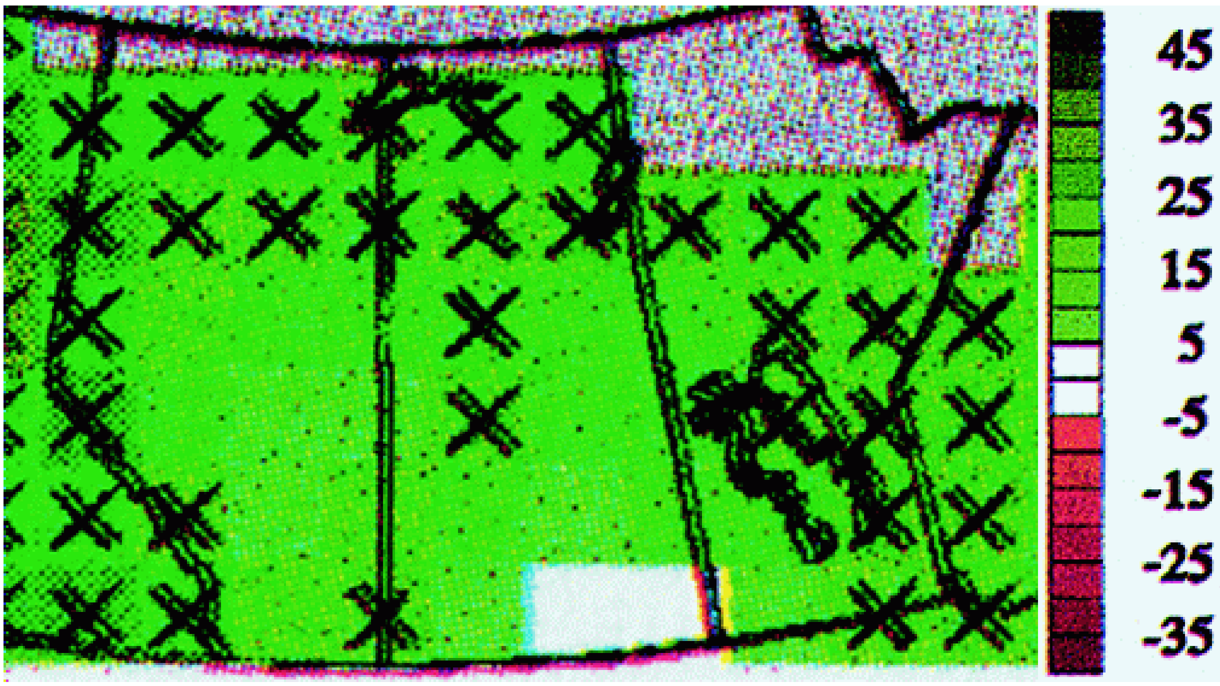

Figure 4: **Trends in annual precipitation totals from 1900-1998** (after Zhang et al. 2000:412). Units are percent change over the 99-year period. Statistically significant trends (5% level) are marked by crosses. Grey means insufficient data.

Precipitation trends for the most recent 49-year period of 1950-1998 have different patterns as compared to the changes over the century. Precipitation increases are generally weaker, and there are more areas of decreases (Zhang et al. 2000). Precipitation totals in the winter have the largest areas of decreases, with changes as large as about -5 to -20% mostly in the grasslands in Alberta and southwestern Saskatchewan.

Snow cover changes over the past century have also been documented. Snow-cover is particularly sensitive to temperature changes. In turn, reduced snow cover area has a positive feedback effect on temperature. Time series data for the western prairies show a long term trend to decreasing snow cover durations since the late 1940s, with a distinct decrease since the 1970s. Snow-cover has been disappearing at a rate of 1-2 days earlier per year over parts of western Canada (Brown et al. 1995).

As for the temperature increases, the snow cover change is not an isolated regional phenomenon, but it is set within a context of a global retreat of snow cover extent. The decrease is most substantial during the spring period, and the mean annual snow cover extent has shrunk by 10% during 1972-1992. The decreasing snow cover extent is shown to be a partial cause of the significant increase in spring surface air temperature over the land areas of the Northern Hemisphere in the past century (Groisman et al. 1994).

Glacier cover has also undergone substantial changes. Time series analyses is hampered by the lack of a comprehensive glacier inventory for the Canadian Rockies, but Luckman (1998) summarized recent results. These glaciers have lost about 25% of their area in the past 100 years, and they are likely smaller now than for any time during the past 1000 to 3000 years. This glacial retreat is thought to be a result of both temperature and precipitation changes (Luckman 1998). Glacial retreat is occurring in the Northern Hemisphere with a few exceptions (Houghton et al. 1996).

PAST TRENDS IN EXTREME WEATHER

Extreme weather events have the potential to cause considerable damage and disruption for ecosystems and socio-economic systems. Extremes events include heat waves, cold spells, droughts, blizzards, intense rainfall, hail-storms, tornados, and dust storms. All of these extremes occur in the Prairies, most of them to a greater extent than in any other place in Canada. A short definition of an extreme is weather that lies outside a region's normal range of weather intensity (Francis and Hengeveld 1998). The patterns of extreme weather events through space and time can be referred to as the climatology of extremes. There are very few studies of the trends in extremes. An overview of the time series of droughts, wet-spells, dust storms, hail storms and tornados is provided here.

Hot and Cold Spells

Abnormally high maximum temperatures in southern Canada show little trend during 1900-1998, but the abnormally low minium temperatures have a strong decreasing trend (Zhang et al. 2000). The low minimum temperatures were defined as temperatures less than the 34th percentile. The pattern of increasing extreme temperatures becomes more predominate during the last 20 years, as more areas are affected by abnormally high temperatures in both the maximum and minimum values. Unfortunately, no information is available by region.

Dry and Wet Spells

Important changes in the variability of daily precipitation events, including extremes have occurred in Canada. Areas affected by abnormally wet conditions have increased, and areas affected by abnormally dry conditions have decreased (Zhang et al. 2000). These trends agree with an overall increase in annual precipitation. Seasonal differences appear, however, as areas affected by both extreme dry and wet conditions increased during the summer. Abnormally dry conditions were defined as precipitation totals less than the 34th percentile, and abnormally wet conditions are defined as precipitation greater than the 66th percentile. Unfortunately, the study area was Canada south of 60° North, so no regional differences can be discussed.

Areas affected by both extreme dry and extreme wet conditions during summer increased (Zhang et al. 2000). These trends indicate an enhanced hydrological cycle, a pattern that is consistent with GCM-based projections driven by increased greenhouse gases.

Increasing trends of all levels of precipitation intensity, ranging from light to heavy, occur across southern Canada (Stone et al. 2000). Increases are concentrated in heavy and intermediate events during the last fifty years with the largest changes in the Arctic. Light intensity precipitation events are defined as greater than or equal to 0.6 mm per day, and intermediate events are greater than or equal to 2.0 mm per day.

Somewhat different patterns appear for the Prairies. Winter has the greatest decrease in the frequency of both light and heavy precipitation events, with changes of -30% in heavy events for the 1950-90 period as compared to the 1960-1990 mean. Summer shows general increases of 30% or less in the light events. Some increases are documented in the heavy events in the summer, but decreases are noted for southern Saskatchewan and Manitoba (Stone et al. 2000).

The monitoring and trend analysis of the more severe dry-spells, or **droughts**, are limited by problems with defining droughts. Confusion also occurs because of the many types of droughts. Various time series of droughts have been graphed for the Prairies, but no trend analyses of droughts were found . For example, the Palmer Drought Severity Index [PDSI], a commonly used drought indicator was calculated for 1908 to 1993 for southern Saskatchewan for July (Maybank et al. 1995) (Figure 5). The time series shows considerable variation, with domination by the classical droughts of the 1930s, 1961 and 1980s. However, there is a slightly higher number of droughts (PDSI less than -2) during the 1960 to 1990 period than for the previous 30 years, even though the later includes the classic dirty thirties' drought. In contrast, the number of wet periods (PDSI greater than 2) appears similar, however, the magnitude of the wet spells was much greater in the earlier period.

Other drought indices are calculated to depict agricultural, waterfowl, and stream-flow droughts. The frequency of various types of droughts for the Prairies appears to be greater during the 1961 to 1990 period as compared to the preceding 30 year period (Figure 5).

More recently, Skinner et al. (2001) calculated the PDSI for the 1925 to 1990 period for both Canada and the United States. The summer (June, July, August) change in PDSI indicates a trend towards drier conditions in southern portions of the grassland region in Saskatchewan and Manitoba and towards wetter conditions elsewhere in the Prairie Provinces (Figure 6). Only the changes for the boreal forest are statistically significant. More comprehensive time series analyses is needed to produce more information about drought trends.

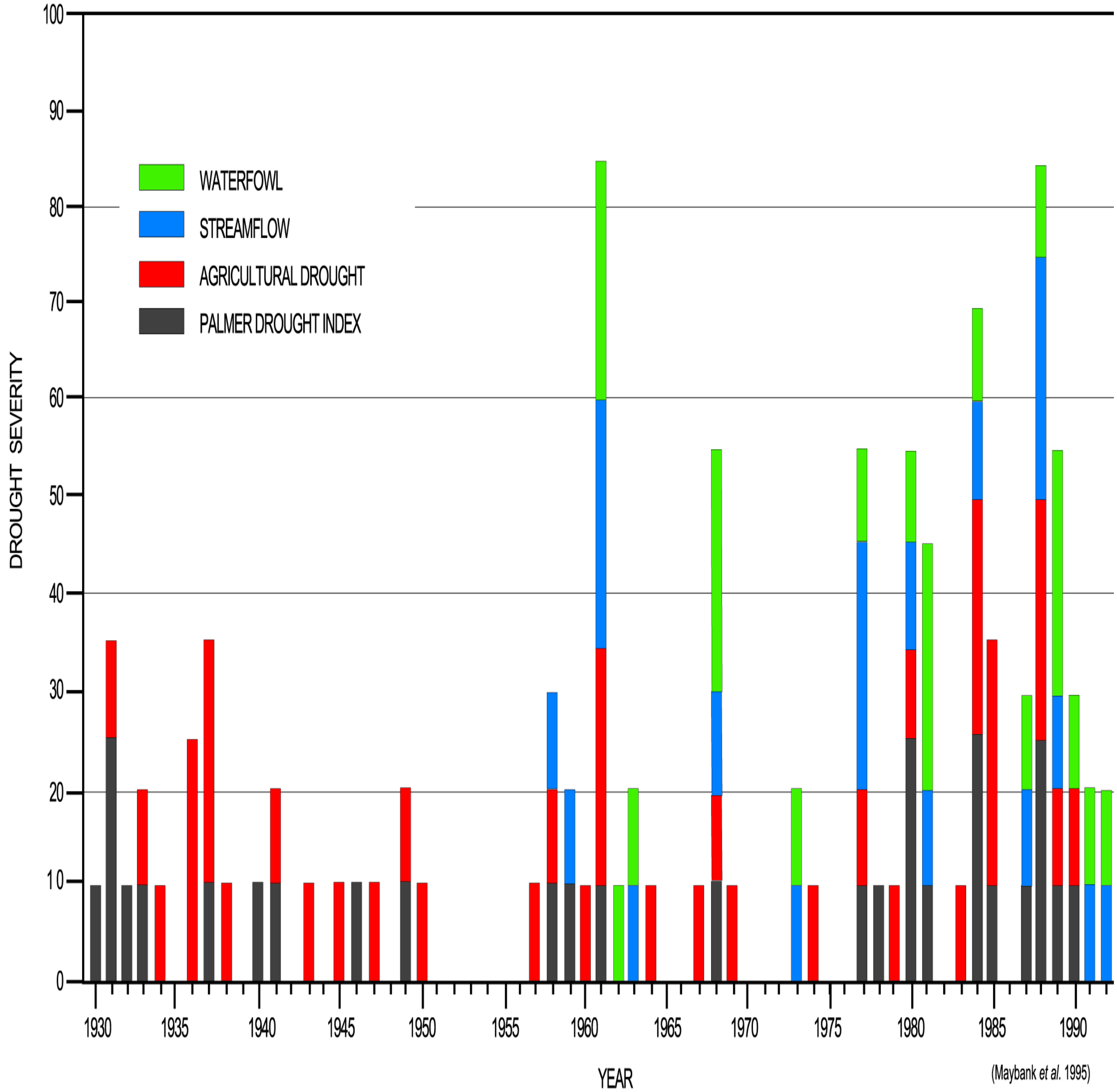

Figure 5: Drought years on the Canadian Prairies, as identified by sector severity (Maybank et al. 1995).

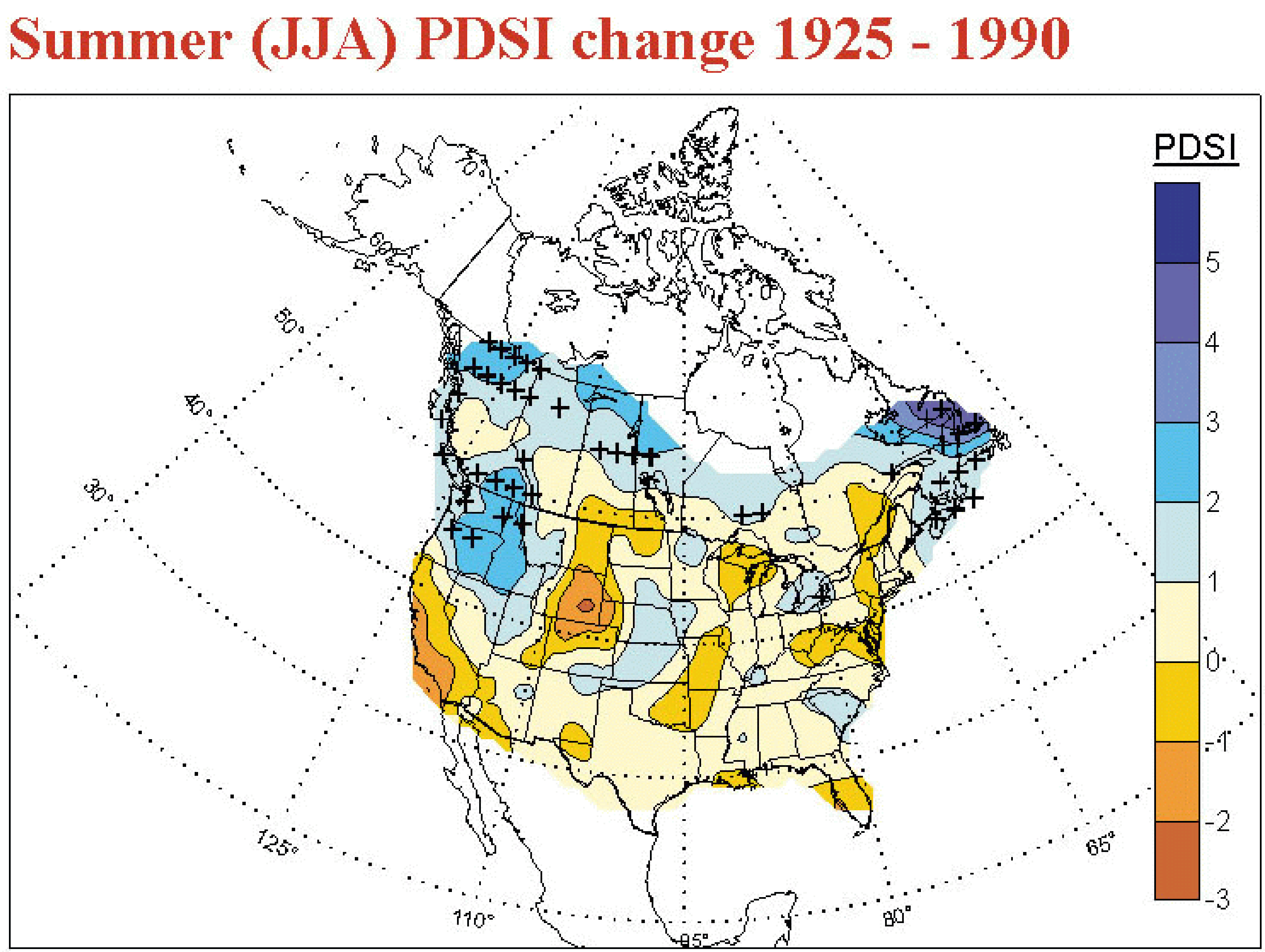

Figure 6: **The change in Palmer Drought Severity Index (PDSI) during the summer (June, July, August), 1925 to 1990 for Canada and the United States** (Skinner et al. 2001). The analysis was of linear trends with removal of lag-1 autocorrelation. Plus signs (+) indicate statistical significance at 95%.

Storms

Time series information for other hazardous climatic extremes such as dust storms, hail storms, and tornados is very limited. The **dust storm** time series documented by Wheaton and Chakravarti (1990) is too short for trend analyses as it is only nine years long, and the frequencies are highly variable. However, dust storm frequencies are linked with drought, and increasing drought frequencies usually mean increasing dust storms (Wheaton 1990). The northward expansion of arid climatic zones may also bring increased dust storms. The secondary maximum of dust storms in the US is located just south of Saskatchewan (Orgill and Sehmel 1976), and may become a more frequent "visitor" to the Prairies as climate zones shift poleward.

A longer time series of **hail storm** data is available for the period 1977-1993 (Etkin and Brun 1999). The regional frequencies of hail frequencies show no trends, except for Alberta. Alberta's hail storms numbers show a significant increase for the period after 1982. This work has not been updated to include the rest of the 1990s, to the author's knowledge.

The **tornado** time series of 1916 to present is considerable longer than the dust storm and hail storm databases, although the database is poor prior to 1980. Etkin (1995) compared the frequencies of the periods before and after 1980 as the sample sizes are adequate for frequency analyses. Western Canadian tornados were found to occur eleven days earlier, on average, for the 1980 to 1992 period as compared to the 1951 to 1979 period. The pattern of tornado occurrence correlates well with mean monthly temperature anomalies. Increasing temperatures tend to bring increased numbers of tornados. This work is a basis for the expectation that tornado frequency would increase with continued warming. A longer warm season also means that more tornados would occur during spring and fall.

Southwest Manitoba and southern Saskatchewan have the second highest risk of tornados in Canada. Canada is second only to the US for top tornado frequencies in the world (Lanken 1996). Saskatchewan averages 7.1 tornado days per year and Manitoba's annual average is 5.0 tornado days for1960-1989. A tornado day is defined as a calendar day with at least one recorded tornado occurrence. Both provinces show upward swings in tornado days over that period, with an especially notable trend of over 3% of the average per year for Saskatchewan. The upward swing could be related to better tornado reporting and enhanced public awareness (Raddatz and Hanesiak 1991) as well as increasing temperatures and warm season length.

Tornados pose extreme risk to life and property. Tornados require close monitoring and appropriate preparedness, especially for areas of relatively high risk such as the Prairies. Updated and improved trend analyses are required to determine the changes in frequency, season length, and spatial patterns of tornados.

CONCLUSIONS AND RECOMMENDATIONS

The process of global warming is underway and is already causing biophysical and likely socio-economic effects. Considerable changes in the climate system have occurred, partly a result of human activities. Much stronger changes have occurred in the Prairies than recorded nationally and globally. Regional warming is already affecting ecosystems, and has the potential to accelerate and cause even stronger effects in the future.

Trends in the main elements of temperature and precipitation, as well as other elements, must continue to be monitored at high quality climate stations. Several more specific recommendations are provided in the previous sections. Updated trend analyses must be undertaken much more frequently and for many more climate variables, as climate change is accelerating. Trends in characteristics of the climate system that affect ecosystem and thus socioeconomic systems must also be determined. These include frost-free season length, growing degree-days, cooling degree-days, as well as extremes such as cold and warm spells, intense rainfalls, floods, droughts, dust storms, tornados, hail, and wind-storms.

ACKNOWLEDGMENTS

Funding was provided by the Government of Canada's Climate Change Action Fund (Agreement A305), the Saskatchewan Research Council (SRC), and Saskatchewan Environment and Resource Management, and the University of Saskatchewan. V. Wittrock, SRC, provided comments. L. Crone, SRC, accomplished the word processing. J. Raven and C. Macleod assisted with the literature searches.

A companion presentation is:
Wheaton, E. and Wittrock, V. 2001. Prairie Climate Change: Past and Future Trends. Invited presentation to the EMAN (Ecological Monitoring and Assessment Network) National Science Conference, Calgary, Alberta, May 4, 2001. Saskatchewan Research Council, Saskatoon, SK.

REFERENCES

Ahmad, Q.K., O. Anisimov, N. Arnell, S. Brown, I. Burton, M. Campos, O. Canziani, T. Carter, S. J. Cohen, P. Desanker, W. Easterling, B.B. Fitzharris, D. Forbes, H. Gitay, A. Githeko, P. Gonzalez, D. Gubler, S. Gupta, A. Haines, H. Harasawa, J.I. Holten, B. Pateh Jallow, R. Jones, Z. Kundzewicz, M. Lal, E.L. La Rovere, N. Leary, R. Leemans, C. Liu, C. Magadza, M. Manning, L. Jose Mata, J. McCarthy, R. McLean, A. McMichael, K. Miller, E. Mills, M. Monirul Qader Mirza, D. Murdiyarso, L. Nurse, C. Parmesan, M. Parry, J. Patz, M. Petit, O. Pilifosova, B. Pittock, J. Price, T. Root, C. Rosenzweig, J. Sarukhan, J. Schellnhuber, S. Schneider, R. Scholes, M. Scott, G. Sem, B. Smit, J. Smith, B. Sohngen, A. Tsyban, J. van Ypersele, P. Vellinga, R. Warrick, T. Wilbanks, A. Woodward, and D. Wratt. 2001. Summary for Policymakers. *In*: McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White (Editors), *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, pp. 1-17. Intergovernmental Panel on Climate Change [IPCC] Working Group II. Cambridge University Press, New York, New York.

Beaubien, E.G. and H.J. Freeland. 2000. Spring Phenology Trends in Alberta, Canada: Links to Ocean Temperature. *Int. J. Biometeorol.*, **44**:53-59.

Beniston, M. and J.L. Innes (Editors). 1998. *The Impacts of Climate Change on Forests*. Lecture Notes in Earth Sciences Series No. 74. Springer-Verlan, Heidelberg and Berlin.

Brown, R.D., M.G. Hughes, and D.A. Robinson. 1995. Characterization of the Long-Term Variability of Snow Cover Extent Over the Interior of North America. *Annals of Glaciology*, **21**:45-50.

Dunn, P. and Winkler, D. 1999. Climate Change has Affected Breeding Date of Tree Swallows Throughout North America. *Proceedings of the Royal Society of London*, **B 266**:2487-2490.

Environment Canada, Atmospheric Environment Service. 1995. *The State of Canada's Climate: Monitoring Variability and Change*. State of the Environment Report No. 95-1. Environment Canada, Downsview, Ontario.

Lanken, D. 1996. Funnel Fury. *Canadian Geographic*, 24-31.

Etkin, D.A. 1995. Beyond the Year 2000, More Tornados in Western Canada? Implications for the Historical Record. *Natural Hazards*, **12**:19-27.

Etkin, D. and S.E. Brun. 1999. A Note on Canada's Hail Climatology: 1977-1993. *International Journal of Climatology*, **19**:1357-1373.

Francis, D. and H. Hengeveld. 1998. Extreme Weather and Climate Change. *Climate Change Digest*. Atmospheric Environment Service, Environment Canada, Downsview, Ontario. 31 pp.

Grassl, H. 2000. Status and Improvements of Coupled General Circulation Models. *Science*,. **288**:1991-1997.

Groisman, P.Y., T.R. Karl, R.W. Knight, and G.L. Stenchikov. 1994. Changes of Snow Cover, Temperature, and Radiative Heat Balance Over the Northern Hemisphere. *Journal of Climate*, **7**:1633-1656.

Gullett, D.W. and W.R. Skinner. 1992. *The State of Canada's Climate: Temperature Change in Canada 1895-1991*. State of the Environment Report 92-2. Atmospheric Environment Service, Environment Canada, Downsview, Ontario.

Hengeveld, H. 1995. *Understanding Atmospheric Change: A Survey of the Background Science and Implications of Climate Change and Ozone Depletion*. Atmospheric Environment Service, Environment Canada, Downsview, Ontario.

Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (Editors). 2001. *Climate Change 2001: The Scientific Basis*. Intergovernmental Panel on Climate Change [IPCC] Working Group I. Cambridge University Press, New York, New York. 881 pp.

Karl, T., R. Knight, and B. Baker. 2000. The Record Breaking Global Temperatures of 1997 and 1998: Evidence for an Increase in the Rate of Global Warming? *Geophysical Research Letters*, **27**(5):719-722.

Lemmen, D., S. McGinn, T. O'Brien, E. Wheaton, and F. Zwiers. 2000. *Climate Variability and Change: Opportunities and Risks*. Presentation to a Prairie Adaptation Research Collaborative (PARC) Workshop. PARC, Regina, Saskatchewan.

Luckman, B.H. 1998. Landscape and Climate Change in the Central Canadian Rockies During the 20th Century. *The Canadian Geographer*, **42**(4):319-336.

Luckman, B.H. and T.A. Kavanagh. 1998. Documenting the Effects of Recent Climate Change at Treeline in the Canadian Rockies. *In*: Beniston, M. and J.L. Innes (Editors), *The Impacts of Climate Change on Forests*, pp. 121-144. Lecture Notes in Earth Sciences Series No. 74. Springer-Verlan, Heidelberg and Berlin.

Majorowicz, J.A. and W.R. Skinner. 1997. Anomalous Ground Warming Versus Surface Air Warming in the Canadian Prairie Provinces. *Climate Change*, in press.

Maybank, J., B. Bonsal, K. Jones, R. Lawford, E.G. O'Brien, E.A. Ripley, and E. Wheaton. 1995. Drought As a Natural Disaster. *Atmospheric-Ocean*, **33**(2):195-222.

Menzel, A. and P. Fabian. 1999. Growing Season Extended in Europe. *Nature*, **397**:659.

Myneni, R.B., C.D. Keeling, C.J. Tucker, G. Asrar, and R.R. Nemani. 1997. Increased Plant Growth in the Northern High Latitudes From 1981 to 1991. *Nature*, **386**:698-702.

Orgill, M.M. and G.A. Sehmel. 1976. Frequency and Diurnal Variation of Dust Storms in the Contiguous U.S.A. *Atmospheric Environment*, **10**:813-825.

Raddatz, R.L. and J.M. Hanesiak. 1991. Climatology of Tornado Days 1960-1989 for Manitoba and Saskatchewan. *Climatological Bulletin*, **25**(1):47-59.

Schwartz, M. and B. Reiter. 2000. Changes in North American Spring. *International Journal of Climatology*, **20**:929-932.

Singh, T. and E. Wheaton 1991. Boreal Forest Sensitivity to Global Warming: Implications for Forest Management in Western Interior Canada. *Forestry Chronicle*, **67**(4):342-348.

Skinner, W.R., K. Heinze, L.A. Vincent, and E. Mekis. 2001. *The Palmer Drought Severity Index as Calculated from the Canadian Historical Climate Database over the 20th Century*. Presentation, Climate Research Branch, Environment Canada, Downsview, Ontario.

Stone, D.A., A.J. Weaver, and F.W. Zwiers. 2000. Trends in Canadian Precipitation Intensity. *Atmosphere-Ocean*, **38**(2):321-347.

Vincent, L.A., X. Zhang, and W.D. Hogg. 1999. Maximum and Minimum Temperature Trends in Canada for 1895-1995 and 1946-1995. *10th Symposium on Global Change Studies*, Dallas, Texas.

Watson, R.T., D.L. Albritton, T. Barker, I.A. Bashmakov, O. Canziani, R. Christ, U. Cubasch, O. Davidson, H. Gitay, D. Griggs, J. Houghton, J. House, Z. Kundzewicz, M. Lal, N. Leary, C. Magadza, J.J. McCarthy, J.F.B. Mitchell, J.R. Moreira, M. Munasinghe, I. Noble, R. Pachauri, B. Pittock, M. Prather, R.G. Richels, J.B. Robinson, J. Sathaye, S. Schneider, R. Scholes, T. Stocker, N. Sundararaman, R. Swart, T. Taniguchi, and D. Zhou. 2001. *Summary for Policymakers - Climate Change 2001: Synthesis Report*. Intergovernmental Panel on Climate Change [IPCC] Working Groups. IPCC, Geneva, Switzerland.

Wheaton, E. 2001. *Changing Climates: Exploring Possible Future Climates of the Prairie Provinces*. Prepared for the Government of Canada's Climate Change Action Fund (Agreement A305). Saskatchewan Research Council (SRC), Saskatoon, Saskatchewan. SRC Publication No. 11341-3E01.

Wheaton, E. 1991. *Global Warming: How could it change Saskatchewan?* Invited presentation in: The University of Saskatchewan's Extension Division's Midtown Plaza Speaker Series: University to the People, September 16, 1991, Saskatoon, Saskatchewan.

Wheaton, E.E. 1990. Frequency and Severity of Drought and Dust Storms. *Canadian Journal of Agricultural Economics* **38**:695-700. Saskatchewan Research Council (SRC) Publication No. E-2330-5-D-90.

Wheaton, E.E. and A.K. Chakravarti. 1990. Dust Storms in the Canadian Prairies. *International Journal of Climatology* **10**:829-837. Saskatchewan Research Council (SRC) Publication No. E-906-42-A-88.

Wittrock, V. and E. Wheaton. 1989. Impact of the 1988 Drought on Migratory Birds: Saskatchewan and Manitoba. *In*: Wheaton, E. and L. Arthur, *Environmental and Economic Impacts of the 1988 Drought: with emphasis on Saskatchewan and Alberta*. Vol. 1. Saskatchewan Research Council, Saskatoon, Saskatchewan.

World Meteorological Organization (WMO). 1999. *Statement of the Status of the Global Climate in 1998*. WMO, Geneva, Switzerland.

Zhang, X., L.A. Vincent, W.D. Hogg, and A. Niitsoo. 2000. Temperature and Precipitation Trends in Canada During the 20th Century. *Atmosphere-Ocean*, **38**(3):395-429.